EXECUTIVE SUMMARY

Nuclear Energy in the United States

The United States currently operates 103 large, commercial nuclear power reactors that provide about one fifth of the Nation's electricity. Since 1977, nuclear electric generation in the U.S. has nearly tripled.[1] Many states depend on nuclear energy for a substantial portion of their electricity. Of all U.S. electricity generating technologies, only coal is more widely used than nuclear energy. As economic growth continues to drive energy demand, and as reserve margins for baseload electric generating capacity continue to shrink, the contribution of these reliable nuclear generating assets to U.S. energy security is becoming clearer.

As the United States completes the deregulation of its electricity business sector, nuclear energy is proving itself to be a highly competitive electricity generation technology. For example, in 1998, the total production costs (sum of operations, maintenance, and fuel costs) for U.S. nuclear power plants averaged 2.13 cents per kilowatt-hour (kWh). This was considerably less than the 2.73 cents/kWh averaged in 1990, showing that nuclear energy plant efficiency has improved dramatically over the past decade. Average nuclear energy production costs in 1998 were only marginally higher than for coal, which averaged 2.07 cents/kWh, and were considerably less than for natural gas at 3.30 cents/kWh and oil at 3.24 cents/kWh.[2] With the asset write-offs that are resulting from deregulation, nuclear and coal-fueled generation have high prospects in the near future of becoming competitive with gas and oil-based generation on a total cost basis.

Nuclear energy is proving to be a safe and reliable source of baseload electricity. All the key indicators of U.S. nuclear energy plant safety and reliability have improved markedly over the past decade—fewer unplanned shutdowns, fewer safety system actuations, fewer forced outages, and higher reliability. The U.S. nuclear industry set a new reliability record of 86.8% capacity factor for 1999. This is in contrast to under 60% in the early 1980s. U.S. nuclear plant performance, as measured by these and other indicators, is among the highest in the world.[3]

U.S. nuclear energy plants use an abundant source of fuel that has minimal adverse environmental impacts when compared with other baseload energy supply options. Nuclear energy's fuel prices are stable and represent a smaller portion of total production costs in comparison to fossil energy costs. Thus, nuclear energy is less sensitive to fuel pricing and fuel market fluctuations, providing the U.S. with a highly reliable and diverse source of energy that serves as a price hedge against more volatile fossil fuels, particularly natural gas.

Plant license renewal (increasing the licensed operating limit of current nuclear power plants by 20 years) is seen by industry as an attractive option to effectively recover more value from current nuclear plant assets and to better assure cost competitiveness on a going forward basis. Two reactors in Maryland and three reactors in South Carolina successfully completed this process with the Nuclear Regulatory Commission (NRC) in 2000 at low incremental costs.

1 Information Digest, 2000 Edition, USNRC
2 UDI for actual data, converted to 1998 dollars by Nuclear Energy Institute
3 Nuclear Energy Institute web site

In addition to helping the economy, U.S. nuclear energy plants are contributing to a healthier environment. Between 1973 and 1999, U.S. nuclear energy plants cumulatively avoided more than 60 million tons of sulfur dioxide and 30 million tons of nitrogen oxide, both of which are pollutants controlled under the Clean Air Act. Over this same period, the Nation's nuclear energy plants also avoided 2.61 billion metric tons of carbon emissions. As much as 90 percent of the carbon dioxide emissions avoided by U.S. utilities during this period was attributable to nuclear energy, with most of the remainder attributed to hydroelectric generation. Also, since 1975, nuclear energy has achieved a higher percentage of total nitrogen oxide reduction than reductions achieved by Clean Air Act requirements.[4] Nuclear energy's avoidance of greenhouse gas emissions and other pollutants is necessary to help the United States meet Clean Air Act requirements and international targets for addressing concerns about potential climate change.

Because of factors such as those discussed above, nuclear energy is an attractive energy source for many other countries as well. An international trend toward expanding the use of nuclear energy is expected, as natural resource conservation, environmental protection, and global sustainable development grow in importance in the decades ahead.

Nuclear energy in the U.S. faces important challenges. Deregulation requires continual improvements in economic performance, while maintaining high levels of safety. Regulatory reform by the NRC presents both opportunities and uncertainties. Nuclear waste management issues must be addressed. Major reductions need to be achieved in the capital costs of new nuclear plants to make private sector investment in them practical. Improvements should be made in current plant reliability, economics, and regulatory processes, to further enhance U.S. nuclear plant performance. In so doing, U.S. utilities will be able to supply safe, clean nuclear-generated electricity to U.S. consumers at even lower cost. Clearly, improvements to existing nuclear energy plants benefit U.S. consumers, the environment, and the U.S. economy.

Nuclear Energy Supply Research and Development: Pathway to Progress

Nuclear energy supply depends on sustained research and development (R&D) to maintain and improve its economic and environmental contributions to society. R&D helps forge technology-based solutions for even better plant performance as well as solutions to safety, regulatory and equipment reliability issues on current plants. R&D also leads to even safer, more economic advanced reactor designs for the future. New technology available from related power sector and other high-tech enterprises could be adapted to nuclear energy plants to maintain a modern, competitive technology base.

Nuclear energy has a relatively limited federal R&D program supporting future development particularly when compared with other energy options. Fossil energy (coal, oil, natural gas), renewable energy, energy efficiency and conservation programs, and fusion energy have had large sustained R&D programs during the last decade. Over the same period, federal funding for nuclear energy was significantly reduced and is a small fraction of the funding for other energy supply R&D categories. Relative to the funding for other energy options, funding for nuclear energy R&D is out of balance, especially considering that nuclear energy is the largest emission-

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free source of electricity generation in the U.S., provides a fifth of the Nation's electricity, and can play an even larger role in meeting the Nation's future needs for economic and environmentally responsible electricity.

Nuclear energy supply R&D is important to U.S. national interests. A strong energy R&D program helps maintain a robust range of options for national energy security, and signals a balanced energy policy that encourages an even playing field in energy markets. It provides the basis for a technology solution to growing environmental concerns over air pollution and greenhouse gas emissions. It contributes to U.S. economic strength and a more favorable balance of trade, and reduces U.S. dependence on foreign fuel supplies. Finally, a strong R&D program gives the U.S. greater technical leverage and credibility to positively influence the nuclear programs of other countries.

For the first time since the Atoms for Peace program initiated nuclear energy research in 1952, Congress and the Administration eliminated funding for commercial nuclear energy R&D in fiscal year (FY) 1998—ending the federal investment in this important option for world energy supply. Funding was reinstituted in FY 1999 in part because of the recommendations supporting the restoration of nuclear energy R&D that were made in November 1997 by the President's Committee of Advisors on Science and Technology (PCAST).

In response to the PCAST report, the U.S. Department of Energy (DOE) formulated two new nuclear energy R&D programs that were funded by Congress: the Nuclear Energy Research Initiative (NERI), initiated in FY 1999 to address longer-term issues facing nuclear energy, and the Nuclear Energy Plant Optimization (NEPO) program, initially funded in FY 2000 and focused on performance of currently operating nuclear plants.

NEPO is a directed program aimed at executing R&D projects contained in the *Joint DOE-EPRI Strategic Research and Development Plan To Optimize U.S. Nuclear Power Plants.* NEPO is a public-private partnership with equal or greater matching funds coming from industry. Recommendations for project selection are made to DOE and EPRI by a Joint Coordinating Committee comprised largely of utility executives, and also including representatives from the Nuclear Regulatory Commission (NRC), the Institute of Nuclear Power Operations (INPO), the Nuclear Energy Institute (NEI), the national laboratories, and the university communities. This Joint Coordinating Committee works in concert with the Nuclear Energy Research Advisory Committee (NERAC), which also advises DOE on nuclear energy R&D, as discussed in Chapter 2.

NERI sponsors R&D on new technologies to address the key issues affecting the future viability of nuclear energy, including the construction costs of future nuclear power plants, remaining concerns regarding safety and proliferation resistance, and the continuing challenges associated with nuclear waste. In responding to these issues, the NERI program funds innovative scientific and engineering research at universities, national laboratories, and individual companies in such areas as advanced reactor and power conversion cycles, low output power and special purpose reactors, proliferation resistance, economics, enhanced safety, advanced fuel, and nuclear waste amelioration.

Public-Private Partnerships in Nuclear Energy R&D

In this era of reduced resources and growing demand for new and competitive technologies requiring reliable electricity supplies, the United States must continue its investment in nuclear energy supply R&D. This investment should be balanced with government investments in other energy supply options.

The Federal Government has a responsibility for maintaining energy security and environmental quality; industry has a responsibility for sustained safe and economic performance of its fleet of nuclear energy plants. Hence, industry and the Federal Government have mutual responsibilities for ensuring a safe, reliable, economic electricity supply for the Nation. Both industry and the Federal Government should ensure that they gain a good return from their R&D investments.

Collaboration between DOE and industry is particularly important for nuclear energy R&D, especially that related to currently operating plants. Resources are limited, and nuclear energy R&D needs are pressing, given the years of minimal federal funding. This environment makes DOE-industry cooperation essential. It demands a thorough planning process that articulates the clear rationale and value of the planned R&D, that shows no overlap or gaps between industry and government R&D, and that carefully prioritizes and executes the work. With limited resources and increasing demand that R&D investments achieve market relevance, DOE-industry partnerships are essential to achieving efficient, highly leveraged, market-driven results. They also can help accelerate the R&D process, better ensure customer needs are met, and help transition government-sponsored R&D effectively to the private sector and into the marketplace.

Figure ES-1. Steam Generator Replacement

License Renewal of Current Plants

License renewal is a central strategic opportunity for operating plants in a deregulated business environment. Not only does license renewal afford the Nation a safe, reliable, and inexpensive alternative to costly new generating capacity additions, but it also influences the R&D planning process, since R&D must support priority national needs.

Nuclear energy plants in the United States are licensed to operate for 40 years. The 40-year license term reflects the amortization period generally used by electric utility companies for large capital investments. It is not based on safety, technical, or environmental issues. The Atomic Energy Act of 1954 permits nuclear energy plants to renew their 40-year operating licenses.

With proper maintenance, major nuclear plant structures and components can operate safely and reliably well in excess of 60 years. Further, experience has shown that most components that do age over a plant's lifetime can be repaired or replaced economically, as many already have been (See Figure ES-1 Steam Generator Replacement).

A nuclear energy plant owner/operator's decision to renew a plant's license is fundamentally based on the plant's projected economic performance, and whether it can meet NRC requirements for license renewal. It involves estimates of future electricity demand, the cost of other electricity supply options and the cost of continued operation of the plant. License renewal provides the plant owner with strategic economic advantages that provide stability to future planning and business operations. License renewal provides a longer amortization period for recovering the plant's original construction costs and the costs of major plant improvements such as steam generator or major piping replacement. License renewal also reduces annual operating costs by lengthening the time available to accumulate necessary decommissioning funds.

From a societal point of view, there is another economic incentive for license renewal. Without it, projected growth in U.S. electricity demand will require replacement of roughly 100,000 megawatts electric (MWe) of baseload nuclear generating capacity in the next 35 years. The cost burden to consumers of prematurely replacing this generating capacity would be very large compared to the relatively modest costs of continuous plant life cycle maintenance and the incremental cost to obtain NRC license renewal.

There is an environmental incentive to increasing the currently licensed term of emission-free nuclear energy plants. If they were to shut down, the most likely sources of equivalent large baseload replacement power in this timeframe would be fossil plants, which emit air pollutants and greenhouse gases and are becoming more difficult to site and license in many parts of the Nation. In the longer term, as older fossil plants are retired, the nation is expected to look increasingly to cost-competitive zero- or minimal-emission alternatives Operation of existing nuclear energy plants for as long as practical through license renewal is key to meeting near-term greenhouse gas emission reduction goals and Clean Air Act requirements.

For these economic and environmental benefits to be realized, a large percentage of today's plants must successfully achieve license renewal. As discussed in more detail in Chapter 1, a high percentage of currently operating plants—approaching 100 percent—are now expected to pursue license renewal—a significant shift from 2-3 years ago when experts believed that many nuclear energy plants might not survive deregulation. It turns out that with appropriate treatment of prior capital investments, annual production costs for nuclear plants are very competitive, and the cost of renewal for a current plant is low compared to the cost of building a new plant. Hence, license renewal of existing nuclear plants is obviously the first choice of a utility that will need to add new capacity and has current nuclear assets. The need for new baseload capacity in the U.S. is increasing due to reduced reserve margins in many regions of the country.

In early 2000, the NRC issued the first nuclear energy plant license renewals for Constellation Energy's two-unit Calvert Cliffs plant and Duke Energy's three-unit Oconee plant. Their licenses were extended 20 years beyond the expiration of the initial license term. Three other companies filed license renewal applications with the NRC in 2000—Entergy for Arkansas

Nuclear One Unit 1, Southern Nuclear Operating Company for Plant Hatch 1 and 2, and Florida Power and Light for Turkey Point 3 and 4. Plant owners at 16 plant sites have notified the NRC of their plans to submit renewal applications for another 22 units by 2003.[5]

So what is the value of R&D as it relates to license renewal? First, R&D programs at DOE and EPRI throughout the 1980s and 1990s established the technical basis for nuclear plant life cycle management and optimized a strategy for long-term plant safety and performance, which helped make license renewal possible. This solid technical foundation enabled industry and the NRC to forge ahead and create the regulatory processes for license renewal. In addition, the ongoing and planned R&D is providing the technical basis to maintain safe, reliable, cost-effective operation over the full, extended license term. R&D leading to new technologies for improving plant performance and advancing risk-informed regulation are producing further opportunities to improve the economic competitiveness of these plants. In the context of license renewal, this means more cost-effective aging inspection, mitigation, and other aging management technologies, improved components to support routine replacement of obsolescent parts, and more risk-informed resolutions of aging issues.

Industry and the NRC agree there are no major unresolved safety issues associated with a 20-year license renewal, and no license renewal issues that require new R&D in order to approve license renewals—as demonstrated by the successful completion of license renewal by five nuclear units at two sites. However, R&D remains a key tool for enhancing, streamlining, and adding confidence to the process, as discussed in Chapter 1.

Goals and Objectives of this Joint Nuclear Energy R&D Strategic Plan

The purpose of this Joint Strategic Plan is to help the Federal Government and the private sector jointly develop and prioritize the requisite R&D needs of commercial nuclear energy for the next five to ten years, based on strategic national goals endorsed by both industry and government. These goals are directly related to preserving and promoting economic strength, energy security, environmental quality, and science and technology leadership. This effort requires:

- Articulating a joint vision for nuclear energy
- Developing R&D objectives that support that vision and these national goals
- Ensuring the proposed R&D objectives and tasks have the support of the user marketplace

This user marketplace will ultimately apply the technology developed; therefore the utility industry must see high value in the proposed R&D and significant benefits in applying the results to its plants. This user marketplace also focuses limited resources in both sectors of R&D that will maximize payback in the long term.

The 1998 version of this plan focused on R&D needs for the next five to ten years, but stated the intention that future updates would expand this goal-based approach into longer term R&D. The utility industry is a proponent of this R&D effort and is capable and willing to support DOE's long-term planning process. This is important to DOE in achieving its dual goals of focusing on longer-range, higher-risk R&D, while simultaneously ensuring that its R&D results will

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demonstrate value to the Nation through strengthening and enhancing the U.S. economy. Given the recent development of a Long-Term Nuclear Technology R&D Plan by the NERAC, DOE and EPRI decided not to expand the Joint Strategic Plan at this time.

The following strategic goals guide the development of this Plan. They serve both the Federal Government's responsibility for energy security and environmental quality, and industry's responsibility for sustained safe and economic performance of its current fleet of nuclear energy plants.

Goal 1: Ensure current nuclear plants can continue to deliver adequate and affordable energy supplies up to and beyond their initial 40-year license term by providing a strong technical basis for long-term operation, by resolving open issues related to aging mechanisms, and by applying new technologies to improve the cost-effectiveness and predictability of the life-cycle management process.

Goal 2: Ensure current nuclear plants can continue to deliver adequate and affordable energy supplies by continuing to develop and apply the best technology to enhance nuclear plant reliability, availability, and productivity, while maintaining an adequate level of protection of the health and safety of the public.

For the next five to ten years, this goal-based approach will enhance the safe, cost-effective operation of current nuclear energy plants, through license renewal and through extended service operation. R&D objectives and related R&D to further improve the reliability and performance of these plants that will contribute to these goals are presented in Chapter 1.

This Plan will be updated annually, or as needed, to serve as the primary strategic planning document for industry and government collaboration on nuclear energy R&D needs.

Scope of this Joint Nuclear Energy R&D Strategic Plan

This Joint Strategic Plan focuses on R&D of common interest to both industry and government that relates to improving nuclear technology for the generation of electricity from currently operating plants. The Plan does not currently include long-term nuclear R&D, and does not include nuclear R&D that is not the responsibility of DOE's Office of Nuclear Energy, Science and Technology (e.g., spent fuel repository R&D). The Plan includes short-term nuclear R&D that industry alone should be or is funding to meet its own responsibilities, as well as short-term and medium-term R&D to be conducted on a cooperatively funded partnership basis to meet the joint responsibilities of industry and government. For R&D of common interest to government and industry, this Plan includes R&D requirements without regard to where the funding will come from or who will conduct the work. This approach provides a definition of strategic R&D needs that is independent of fluctuations in industry and federal funding decisions.

The scope and organization of this Plan are needs-driven, with recognition of the need for appropriate fiscal restraint. For this reason, the Joint Strategic Plan targets the DOE funding levels recommended by PCAST in their November 1997 report to the President on federal energy R&D needs. These levels are modest in comparison to the other energy supply R&D

budgets recommended by PCAST and proposed by DOE. This needs-driven approach was focused heavily on short- and medium-term R&D in the first year of this Joint DOE-EPRI R&D Plan, and now focuses more on the medium term.

This Plan supports NEPO program planning and execution. It also provides a baseline set of R&D needs that can be used in both the NERI and NEPO program approaches (proposer-driven and peer review selection process; market-driven and prioritized with industry cost-share, respectively). It directly addresses the PCAST recommendation for R&D in support of the continued operation of current nuclear energy plants (i.e., NEPO). In addition, although NERI is aimed at addressing the future issues facing nuclear energy, it is possible that NERI projects could benefit from considering the R&D needs of current plants as a point of departure.

No attempt has been made to eliminate R&D requirements from this document based on year-to-year funding projections. This is important to the R&D prioritization process, which benefits from a more complete accounting of all priority R&D needs, and which enables DOE and EPRI to make informed decisions on priorities each year. Also, no attempt has been made to structure this Plan to match current or future DOE or EPRI R&D program organization or budget line item allocations, which can change from year to year for reasons other than strategic R&D needs. Rather, this assessment of required nuclear energy R&D will remain stable during fluctuations in DOE/EPRI funding levels, as well as during programmatic changes by DOE and EPRI, the Office of Management and Budget, and the Congress during the appropriations process.

For FY 2000 and 2001, DOE recommended and Congress approved funding for NEPO of $5 million each year. This is below the PCAST proposed funding level of $10 million annually. Neither NERI nor NEPO have been funded to the levels recommended by PCAST.

Plan Organization

Chapter 1 provides a needs-based development of the Issues, Goals, and Objectives for nuclear energy R&D. Chapter 2 describes the Implementation Plan. Chapters 3, 4, and 5 present the elements of this R&D plan that support the goals and objectives, organized as follows:

Chapter 3 - R&D for Managing Plant Aging: This chapter covers the R&D required for long-term, cost-effective management of various material degradation phenomena that are important to the economic operation of current plants. Component and structure material degradation occurs in nuclear plants as a result of long-term operation and exposure of materials to harsh environmental conditions. Material degradation occurs in harsh conditions including radiation and elevated temperature and pressure environments in the reactor pressure vessel, reactor internals, steam generator tubes, system piping, structures, and electrical cables. These components incur degradation over time in the form of corrosion, heat and stress-related fatigue and cracking, and reductions in fracture toughness due to neutron irradiation and thermal embrittlement.

These material degradation mechanisms are subject to monitoring programs today. Even though none of these aging phenomena are obstacles to a plant-specific application for license renewal by the NRC, they can greatly affect the economics of existing plants. R&D will provide a better

understanding of significant degradation mechanisms and how they occur, enabling development of generic, cost effective aging management strategies which will provide capabilities to more effectively manage the degradation through either prevention, detection or repair. Further, the inspection, repair, and performance prediction technologies developed have important applications to nuclear plants around the world, as well as other industries, giving the U.S. a strong global leadership position in safe, economical life cycle management technology.

Chapter 4 - License Renewal: In the initial 1998 version of this Plan, this chapter was concerned with the demonstration of the license renewal process. At that time, no U.S. plant had formally applied for license renewal, and industry and DOE anticipated that the regulatory process for license renewal could be costly and protracted. To facilitate license renewal applications, this part of the Joint R&D plan was intended to reduce the uncertainty in the licensing process by supporting four design-specific applications. Although the license renewal process is far from streamlined, it is clear today that joint DOE-EPRI funding is not needed to demonstrate the license renewal process in order to encourage individual license renewal applicants.

Therefore, no funding has been provided for this purpose, and none is anticipated in the short term. However, this chapter is being retained in the Plan as a "place-holder" to account for the possibility that a future update to this Plan might require joint funding support to some generic aspect of the licensing process. All R&D activities that support license renewal indirectly (aging management technologies and generation optimization technologies) are covered in Chapters 3 and 5, respectively.

Chapter 5 - Generation Optimization: This chapter focuses on improving the economic performance of current plants through development of technologies that will improve capacity factors, lower operating costs, ensure long-term economic performance, and increase power output where excessive design or regulatory margins exist in licensed plant power limits. This chapter takes advantage of modern computer and telecommunications technologies that can enhance the performance of nuclear plants. R&D in this category will produce new technology applications that will address growing obsolescence issues with older technologies (e.g., analog-based control systems), make nuclear plant operation and maintenance processes more economical, and improve overall plant reliability and power output. Advanced technologies to enhance human performance are also included in this chapter.

Other advancements in high-efficiency nuclear fuel technology and options to improve plant capacity factors are possible. To achieve regulatory acceptance of these new technologies, performance demonstrations will be an integral part of this R&D effort. This chapter is organized by the following technology areas: digital instrument and control systems; advanced sensor technologies; advanced monitoring, diagnostic, and control systems; organizational factors and human performance; advanced safety analyses; advanced nuclear fuels; and risks. It should be noted that some of the technologies developed could be applied to other industries, thereby multiplying the value obtained.

Summary: Benefits of Nuclear Energy R&D and of the NEPO Program

Robust nuclear energy R&D and a successful NEPO Program will benefit the U.S. energy portfolio and expanding economy by:

- Maintaining a prudent, balanced range of options for national energy security and signaling a balanced energy policy that encourages an even playing field in current and future energy markets

- Providing a major contribution to reduction of air pollution and greenhouse gas emissions

- Contributing to U.S. economic strength, balance of trade, and high-tech domestic jobs

- Providing global leadership in a critical technology area that requires U.S. influence (e.g., safety and non-proliferation policy) to promote our vital national interests and to fulfill our obligation under the Non-Proliferation Treaty for support of peaceful-use technologies

- Capitalizing on past investment in operating nuclear plants and infrastructure through safe and cost-effective license renewal, supported in part by nuclear energy R&D

- NEPO, although a modest program, is aimed at making a positive impact in the U.S. by:
  - Focusing R&D on U.S. climate change goals that require useful results that yield large payoffs in the short term
  - Focusing R&D on the bottom line, i.e., reducing costs, improving performance, extending plant operating life
  - Helping reduce the uncertainties associated with nuclear plant license renewal and improving the economics for a 60 year life at all plants

- Public-private partnership is essential to achieving these near-term goals because:
  - Major utility executive participation assures market relevance in the R&D decision process
  - Partnership accelerates the R&D process and the transfer of results to the marketplace
  - Partnership permits streamlined decision processes, contractor selection, etc.
  - Industry cost-sharing maintains a high level of industry involvement in guiding government R&D programs